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Power density improvement of the power conditioning circuit for combined piezoelectric and electrodynamic generators

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Abstract. In this study, we report a power management circuit for a combined piezoelectric-electrodynamic generator. A piezoelectric element is bonded to a spring steel cantilever beam and a magnet, used as tip mass, oscillates through a coil. This principle creates the combined generator. A test setup has been created to automate the characterization of the piezoelectric generator and its power management circuit. Three different power management circuits for the piezoelectric part of the combined generator have been analysed: a bridge rectifier, an SSHI circuit with an external inductance and an SSHI circuit which utilizes the coil of the electrodynamic generator as circuit element. The three circuits are compared in terms of their output power, efficiency and power density. The SSHI circuit with an external inductance has the highest output power and efficiency, followed by the SSHI circuit with the electrodynamic generator coil. The power density of the bridge rectifier is the highest but for higher efficiency the power density of the SSHI circuit with the coil of the electromagnetic generator reaches the best results.

1. Introduction

Ambient vibrations are an energy harvesting source available in several application scenarios. An inertial generator converts the environmental vibrations into electrical energy to supply low power electronic circuits like micro-controllers, sensors and RF communication modules. The electrical output power of an energy harvesting power supply can be improved on the generator side as well as on the power management circuit side. Moreover, power density is usually employed for a comparison between inertial generators since output power scales directly with the volume. However, power density has not been a figure of merit for the power management circuit until now.

This paper presents a coupled piezoelectric-electromagnetic energy harvester that converts ambient vibrations into electrical vibrations increasing the power output density compared to a standalone piezoelectric (PEG) or electrodynamic generator (EDG) [1].

Piezoelectric generators provide AC power that has to be rectified. Nonlinear circuits can be more efficient than full-wave rectifiers when the inertial generators are excited at their resonant frequencies [2]. Thus, the paper compares the power harvested by the piezoelectric part of the coupled generator employing a diode full-wave rectifier and a synchronized switch harvesting on inductor (SSHI) circuit [3]. By using the inductor of the electrodynamic generator in the SSHI circuit, the output power density of the power management circuit is increased since no extra inductor is required.

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The structure of the paper is as follows. Section 2 describes the coupled piezoelectric-electromagnetic generator and the setup of the measurement system. Section 3 describes the standard power management circuit. Section 4 shows the advanced power management circuitry employing an external coil and employing the coil of the electrodynamic part of the generator, respectively. Finally, Section 5 compares the different power management circuits and draws the main conclusions achieved in the paper.

2. Measurement setup

A schematic of the piezoelectric-electrodynamic generator (PEDGen) presented in this paper is shown in **Figure 1**. The piezoelectric generator part consists of a unimorph cantilever beam with tip mass. A permanent magnet has been employed as tip mass and together with a coil around it forms the electrodynamic generator. Therefore, an inertial generator based on the piezoelectric and electrodynamic effect has been presented.

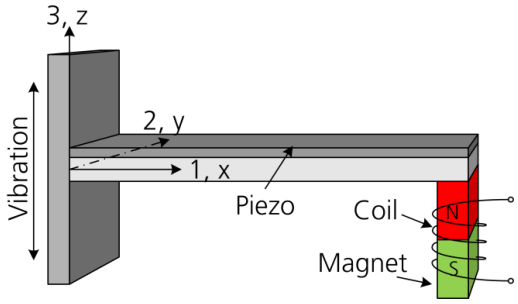

Figure 1. Schematic of the piezoelectric-electromagnetic energy harvesting generator (PEDGen).

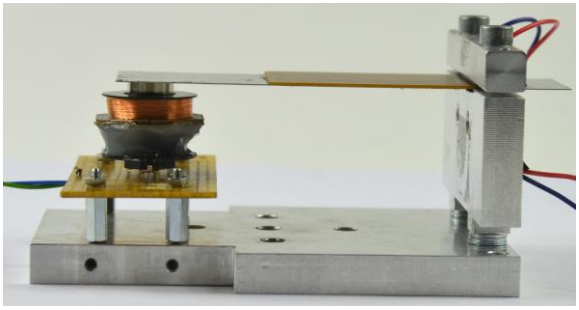

Figure 2. Picture of the piezoelectric-electromagnetic generator prototype.

Figure 2 displays the prototype of the piezoelectric-electromagnetic prototype used for testing in the paper. A P-876.A15 DuraAct transducer by PI Ceramic with the dimensions 61x35x0.4 mm^3 is glued to a 97x30x0.3 mm^3 spring steel beam. A neodymium magnet (NdFeB) that weighs 5 g and has a diameter of 12 mm and a height of 6 mm is placed at the free end of the cantilever beam. The coil has 1500 windings with 0.15 mm enameled copper wire resulting in an electrical resistance of 187 Ω and an inductance of 47 mH.

Figure 3 shows the combined output power at the resonance frequency of 42.44 Hz of the piezoelectric-electromagnetic generator without rectification. The maximum output power is 282 μW at the load resistances R_{EDG} = 3.9 $k\Omega$ and R_{PEG} = 48.9 $k\Omega$. This and all following measurements were performed with an amplitude of 0.1 g since it can be observed that many real ambient vibrations have an amplitude around this value [2].

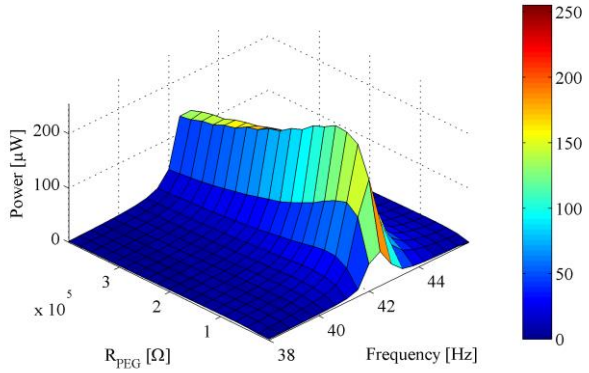

Figure 3. AC power output of the piezoelectric generator.

3. Bridge rectifier

The commercially available power management circuits for piezoelectric generators utilize a bridge rectifier for the rectification stage, e.g. [4]. For this reason, the first measurements are done with a bridge rectifier.

Compared to the AC power with no losses in power management, the bridge rectifier reaches an efficiency of $\eta = 80$ % at the resonance frequency and optimum load resistance without impedance matching. Note that this number is not the efficiency of the circuit but the ratio of available AC power compared to the rectified DC power. This is the reference measurement which means that any advanced or improved power management circuit should deliver more power or rather have a higher efficiency than the bridge rectifier. Otherwise, there is no reason to use a more complicated circuit that utilizes more components and needs to create switching signals for active parts and power them. The effect of the nonlinear circuits on the output power depends on the kind of piezo and on the mechanical setup [5].

4. SSHI circuit

A more advanced power management for piezoelectric generators is the SSHI circuit. It allows a higher efficiency for the rectification stage. The circuit depicted in **Figure 4** is a modified parallel SSHI circuit presented by [3].

The SSHI circuit uses an inductance, which is by far the biggest component of the power management circuit. This is a big disadvantage for miniaturizing the circuit and also because inductances of such high values are relatively expensive.

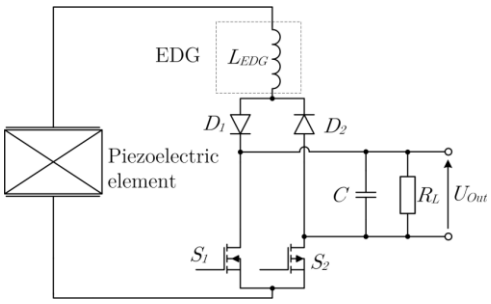

Figure 4. SSHI circuit using the EDG coil.

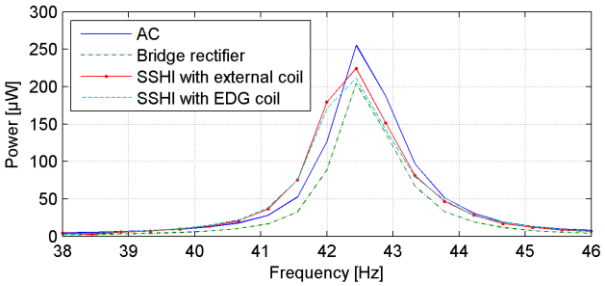

Figure 5. Power output comparison.

The proposed circuit in **Figure 4** utilizes the coil of the electrodynamic generator as the inductance. This is possible because the voltage on the piezo and the induced voltage in the coil have a 90° phase shift. The piezoelectric generator has its maximum voltage at the turning point of the vibration where the mechanical stress is maximum. The electrodynamic generator has its maximum voltage at the highest speed of the magnet, which happens exactly between the two turning points. The results are compared against an SSHI circuit using an external inductance ($L = 48\ mH$ and $R = 190\ \Omega$). The values of the inductance of the electrodynamic generator are $L_{EDG} = 40\ mH$ and $R_{EDG} = 187\ \Omega$.

5. Conclusions and future work

Table 1 and **Figure 5** show the comparison of the different measurements. The AC measurement can be considered as the reference measurement that delivers the most power. If a circuit matched this power, it would have an efficiency of 100 %.

It is clear from **Table 1** that the SSHI circuit has advantages over the standard bridge rectifier topology. With an external inductance, an improvement of 10 % and with the EDG coil an improvement of 3.4 % over the bridge rectifier is possible for this generator.

Table 1. Comparison of measurements

	AC	Bridge rectifier	SSHI external inductance	SSHI EDG coil
f_{Res}	42.44 *Hz*	42.44 *Hz*	42.44 *Hz*	42.44 *Hz*
P_{Out}	255 μW	204 μW	224 μW	211 μW
R_{Opt}	92.8 $k\Omega$	137 $k\Omega$	100 $k\Omega$	110 $k\Omega$
η		80 %	88 %	83 %
L_{SSHI}			48 *mH*	40 *mH*
R_{SSHI}			190 Ω	187 Ω
Power density		1.17 $\mu W/mm^3$	0.42 $\mu W/mm^3$	0.56 $\mu W/mm^3$

The power density of the bridge rectifier is the highest for the three power management solutions, as it requires only minimal board space. Since there is no need for a control circuit or inductance, it has the smallest footprint. If an advanced rectification circuit is employed, the utilization of the EDG coil for the power management significantly increases the circuit's power density as the inductance is by far the biggest circuit component.

A 33 % increment in power density, compared to the SSHI circuit with an external inductance, can be achieved when using the EDG coil.

A power management circuit for the piezoelectric part of a hybrid piezoelectrodynamic generator has been presented. The improvement over the usual SSHI circuit is the utilization of the electrodynamic generator as a circuit component instead of using an external inductance. That way the power management can be realized in a smaller footprint.

A comparison of the different power management circuits has been given with respect to their efficiencies and improvements over the other solutions.

Future work will be developing a power management circuit for the whole generator, which will extract the power of the electrodynamic generator and store the power of both generators in the same storage element. The power density of a combined power management can then be compared to state-of-the-art techniques.

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